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AERODYNAMIC SIZE DISTRIBUTION OF SUSPENDED PARTICULATE MATTER IN THE AMBIENT AIR IN THE CITY OF CLEVELAND, OHIO

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16. Abstract
The City of Cleveland Division of Air Pollution Control and NASA Lewis Research Center are jointly studying the chemical and physical characteristics of the suspended particulate matter in Cleveland. As part of the program, measurements of the particle size distribution of ambient air samples at five urban locations during August and September, 1972 have been made using high-volume cascade impactions. The distributions were evaluated for lognormality, and the mass median diameters compared between locations and as a function of resultant wind direction. Junge-type distributions were consistent with dirty continental aerosols. About two-thirds of the suspended particulate matter observed in Cleveland is less than 7 μm in diameter.

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SUMMARY

As part of a cooperative program being carried out by the City of Cleveland Division of Air Pollution Control and NASA Lewis Research Center to study the chemical and physical characteristics of the suspended particulate matter in Cleveland, measurements have been made of the particle size distributions at five different locations throughout the months of August and September, 1972. High-volume cascade impactor heads operating on conventional high-volume samplers were used for the study. Sampling locations were chosen to represent contrasting urban environments: industrial, commercial, mixed light industrial-residential-commercial to the west of the city center, and a similar site to the east. A total of twenty-one 24-hour samples were obtained at each of the five sites. The mass median diameters show statistically significant variations between sites. Among these contrasting environments, the average lognormal distribution of particle diameters in micrometers was 37 percent by weight above 7, 15 percent by weight from 3.3 to 7, 7 percent by weight from 2 to 3.3, 10 percent by weight from 1.1 to 2, and 31 percent from 1.1 to the approximate 0.01 limit of the backup filter. Examination of the mass median diameter at each site as a function of the prevailing resultant wind direction showed that values from 2.0 to 6.8 micrometers were obtained depending on the site and the wind direction with respect to the location of sources. The largest mass median diameter was associated with an industrial source and the smallest with residential areas. The mass median diameters obtained in this work are significantly higher than results based on the National Air Surveillance Network, but agree well with more recent work done under similar conditions. The reasons for the differences are discussed.

Junge-type distributions calculated from the composite data at each site assuming unit density lead to values for the parameter β of from 2.1 to 3.0, consistent with the distribution in dirty continental aerosols.

INTRODUCTION

As part of a cooperative program being carried out by the City of Cleveland Division of Air Pollution Control and the NASA Lewis Research Center to study the chemical and physical characteristics of the total suspended particulate (TSP) matter in Cleveland, measurements have been made of the particle size distributions of ambient air samples at five locations through the months of August and September, 1972.

The determination of TSP concentration by high-volume sampling gives an estimate of air quality with respect to particulate material. The use of cascade impactors to determine the aerodynamic size distribution of suspended particulates allows an estimate to be made of the potential burden of these pollutants on the respiratory system. The deposition of particles in the respiratory system as a function of their size and other physiological factors has been reviewed and discussed (refs. 1 and 2).

The use of high-volume cascade impactors which mount on standard high volume air samplers[1], provides a convenient method of obtaining the aerodynamic size distribution of suspended particulates. The results can be directly related to data obtained for TSP with the standard high-volume air sampler (ref. 4).

In this work the aerodynamic size distributions of particulates at five sites having contrasting and representative urban environments in the city of Cleveland, Ohio were studied. Sampling locations were chosen to represent industrial, commercial, mixed light industrial-residential, residential-commercial to the west of the city center and a similar site to the east. A total of twenty-one 24-hour samples were obtained at each of the five sites. The size distributions were analyzed in terms of both daily values and values corresponding to resultant wind directions encountered during sampling.

[1]The high-volume samplers used conform to E.P.A. (ref. 3) and ASTM D2009 specifications.

EXPERIMENTAL

Site Selection

The City of Cleveland Division of Air Pollution Control maintains a network of 21 stations for the purpose of monitoring the air quality in the City of Cleveland, Ohio. NASA Lewis Research Center in cooperation with the city augments 16 of these stations to study the chemical and physical characteristics of the suspended particulate matter. Five of these stations were selected for size distribution measurements as follows:

Site 1. - 2785 Broadway, an industrial location, 4 kilometers southeast of the city center, on the roof of a building 6 meters above the ground having a total elevation of 186 meters above sea level.

Site 2. - 3701 East 71st Street, a light industrial-residential location, 8½ kilometers southeast of the center of the city, on the roof of a building 18 meters above ground having a total elevation of 241 meters above sea level.

Site 3. - 16210 Lorain Avenue, a residential-commercial location, 10 kilometers west of the city center, on the roof of a building 10 meters above ground having a total elevation of 243 meters above sea level.

Site 4. - East 105th and Superior, a residential-commercial location, 6½ kilometers east of the city center, on the roof of a building 9 meters above ground having a total elevation of 202 meters above sea level.

Site 5. - 1365 East 12th Street, a commercial location 1½ kilometers east of the center of the city, on the roof of a building 20 meters above ground having a total elevation of 193 meters above sea level.

A more detailed description of each site as a function of the wind vectors encountered is given in the appendix.

Sampling Procedure

The suspended particulates were sampled for four 24-hour periods a week, Monday through Friday noon during August and September, 1972. Commercial (2000 Inc.), high-volume 9.44×10^{-3}-cubic-meter-per-second (20-ft^3/min), four-stage cascade impactor heads with a backup filter were used in conjunction with

standard high-volume air samplers. The samplers were equipped with pressure transducers, flow recorders, variable voltage transformers, and on/off timers. The impactor used provides collection in five aerodynamic size ranges: greater than 7 micrometers, 3.3 to 7 micrometers, 2.0 to 3.3 micrometers, 1.1 to 2.0 micrometers, and from 1.1 micrometers to the backup filter limit of about 0.01 micrometer. The impactor was tested for effective cutoff diameter (ECD) by comparison with a low-volume, 4.72×10^{-4}-cubic-meter-per-second (1-ft^3/min) impactor which has been calibrated by several investigators (ref. 3) and used in routine sampling. The high-volume impactor has been described and field tested by Burton et al. (ref. 3).

The flow rates were checked in the laboratory before use in the field. After assembly of the impactor the pressure drop across the unit was monitored with an oil manometer, attached to a small tap provided for the purpose, to set the flow rate at 9.44×10^{-3} cubic meter per second (20 ft^3/min). Comparison of the pressure drop across the impactor to that across the previously calibrated orifice at the exhaust of the high-volume sampler provided a way of setting the desired flow. Flow adjustments were made with the variable voltage transformer. In all cases the results agree to within 2 percent of the calibration chart supplied by the manufacturer. The volume of air sampled was obtained by observing the flow rate by means of a manometer at the time of start up and shut down and was found to vary by not more than 2 percent. A recording of the flow rate was used to observe any deviations in the flow during the run which was nominally 24 hours. Within the limits of the recorder (±5 percent), no flow rate changes were observed.

The samples were collected on 0.30-meter- (12-in.-) diameter glass fiber filter impact surfaces (manufactured by Gelman Instrument Co.) marketed by the manufacturer of the impactor. The backup filter was a standard 0.20- by 0.25-meter (8- by 10-in.) Gelman glass fiber and, as in the case of the impactor surfaces, had a pH of 6.5. A blank filter was used to indicate any weight change due to ambient humidity variations in the weighing room. No weight changes greater than 0.1 milligram were observed with the blank filter and all weight increases in sample filters were assumed due to particulate matter. The weighing room typically had a relative humidity of less than 50 percent and therefore no corrections are needed for moisture adsorption on the particulate matter (ref. 5).

RESULTS AND DISCUSSION

Since particle sizes usually follow a lognormal distribution, the data are most conveniently displayed by plotting the logarithm of the ECD for each stage as a function of the cumulative percent mass less than or equal to each stage on a normal probability (percentile) scale. The best fitting straight line can be obtained by a least-squares linear regression from which the mass median diameter and standard geometric deviation can be obtained. By visual inspection about 92 percent of all the distributions obtained in this work were adequately represented by the lognormal distribution. That some of the data deviates from a lognormal distribution is not unexpected since such a distribution is a statistical observation and not all data can be expected to conform to it (ref. 6).

Table I summarizes the results: the dates sampled, the resultant wind direction, mass median diameter (MMD) which is the particle diameter found at the 50 percent mass cumulative point, the standard geometric deviation (ref. 7) calculated as the ratio of the MMD to the diameter found at the 15.87 percent mass cumulation point, and the total particulate concentration.

Composite size distributions at each site were obtained from the average cumulative percent mass less than or equal to each stage of all samples collected. The results are plotted as described previously and are shown in figure 1. The average MMD's at sites 1, 2, 3, 4, and 5 are 4.4, 2.4, 2.7, 3.0, and 3.9 micrometers, respectively. The percent by weight distributions at the five sites at one standard deviation are 37±5 percent of the particulates above 7 micrometers diameter, 15±2 percent from 3.3 to 7 micrometers, 7±2 percent from 2.0 to 3.3 micrometers, 10±3 percent from 1.1 to 2.0 micrometers, and 31±5 percent below 1.1 micrometers. This implies that about 37 percent by weight of the suspended particulates in Cleveland are in a size class considered relatively "non respirable" and the potential impact on the respiratory system (refs. 1 and 2) is independent of the location. The depth of penetration of particles in the respiratory tract varies considerably with aerodynamic particle size, and particles greater than 10 micrometers in diameter have been found to be generally nonrespirable (ref. 2). It should be noted that the respiratory system does not provide a sharp cutoff, and a small but finite penetration of $\geq$10 micrometer particles is probable. Trace elements and compound information is an essential ingredient for a comprehensive assessment of impact on

human health and is the subject of present research in this laboratory.

It is of interest to examine the single day results listed in table I to establish whether the differences in mass median diameter observed are statistically significant, more precisely, whether the MMD's observed belong to the same or different statistical distributions. This was accomplished by applying Friedman's significance test (ref. 8) to the data at the five sites on the 9 days for which the data set is complete. A value of 18.1 was obtained for chi squared which demonstrates that there is a greater than 99 percent chance that the differences in MMD's are significant. In the case of the comparisons of MMD at sites 1 and 2 and 2 and5 the Friedman test was indeterminate because of insufficient data so the test for paired observations, namely student's t test, was used for these pairs of sites. Sixteen pairs and 15^{0} of freedom for sites 1 and 2 and 19 pairs and 18^{0} of freedom for sites 2 and 5 gave values for t of -5.46 and 3.65, respectively. This shows that there is a better than 99 percent chance that the MMD's are different (ref. 9) in these cases also.

The effect of wind direction on MMD was also examined at each site to seek source specific characteristics. This was done by segregating the samples at each site with respect to the resultant wind direction prevailing at the time of sampling. For the days sampled the majority are included in four sectors: 30^{0} to 50^{0}, 180^{0} to 190^{0}, 230^{0} to 250^{0}, and 340^{0} to 360^{0} (see table I). The resultant wind directions used were those reported by the National Weather Service at Cleveland Hopkins Airport (CLE). The wind directions for a given sampling period were assumed to be independent of site location since the resultant wind direction at two other wind stations A and B agree to $\pm 12^{0}$ with CLE as shown in table II. The locations of the wind stations are shown in figure 2.

The average MMD for each wind sector at each site is displayed on a map of the city in figure 2. Two sites, 1 and 4, show directional differences in MMD. As noted in appendix which describes the environment of each site corresponding to the wind sectors, the west and south directions which show high MMD for site 1 cover a heavy industrial region with a large pile of iron ore within 0.1 km west of the site. Site 4 with a high MMD from the east corresponds to an industrial area. Site 5 has relatively high MMD's from all four directions. This site is surrounded by commercial buildings. Sites 2,3, and the remaining sectors of site 4 are equivalent and the areas are representative of residential and small commercial establishments. Here again an accurate determination of source origin requires trace element and com-

pound information which is being obtained currently at the NASA Lewis Research Center.

It is appropriate to compare the MMD results obtained in this work with that reported by others in similar environments. Lee and Goranson (ref. 10) found MMD's for urban particulates to be in the submicron range, an order of magnitude smaller than the results of this work. This discrepancy appears to be related to their reliance upon calculated ECD's (ref. 11) instead of performing a physical calibration of the impactor used which was run at a different flow rate than designed. Also, aluminum foil was used as the impactive surface and this has been shown to permit "bounce off" of particles from the stage where they are supposed to be collected and are actually collected on a lower stage. This results in heavy biasing of the distribution toward the submicron size (ref. 3). More recently Brown (ref. 12) using equipment similar to that used in this work studied three sites at Wright Patterson Air Force Base in Ohio: at the end of an active runway and downwind of a coal burning power plant, near a coal burning power plant and base exchange, and near an entry gate experiencing heavy automobile traffic. Values for MMD of 3.8, 3.2, and 4.1 micrometers, respectively, were found, which agree well with the Cleveland results.

The composite mass size distribution were also used to derive a Junge-type number size distribution (ref. 13, p. 116). The data limits the range of particle radius from 0.1 to 10 micrometers. Fortunately this range is sufficient to calculate the Junge parameter β from the following equation since the linear portions on a log-log plot occur for radii >0.1 micrometer for typical atmospheric aerosols:

$$\frac{dN}{d \log r} = Cr^{-\beta} \tag{1}$$

where N is the total number concentration of aerosol particles of radius smaller than r, r is the radius of particles in micrometers, and C and β are dimensionless constants obtained from the intercept and slope, respectively, of the Junge plot. In converting the particle mass to particle number a spherical shape and unit density was assumed since that is the basis for the calibration of the impactor. The accumulated mass was taken over small finite increments of particle radii (0.3 μm) to estimate the differential number in that size range. Figure 3 is a plot of equation (1) for each site on log-log- coordinates from which β is

obtained from the slope. Values of 2.6, 3.0, 2.9, 3.1, and 2.6 are obtained for β for sites 1, 2, 3, 4, and 5, respectively. The values around 3.0 agree well with values Junge obtained for dirty continental aerosols. The lowest β value of 2.6 indicates a distribution with a higher concentration of larger particles (ref. 13, p. 145). Visibility range determinations (ref. 13, p. 144) from 1 to 100 kilometers confirm the power distribution law with β of from 2.5 to 3.5, sometimes times higher, as a world-wide phenomena for a wide range of continental conditions. Lateral displacement in figure 3 is, of course, sensitive to the density chosen. Site 1 shows up as being anomalous in this regard and could be accounted for if the time mean density were greater than unity which is not inconsistent with its surroundings.

CONCLUSIONS

As part of a cooperative program being carried out by the City of Cleveland Division of Air Pollution Control and NASA Lewis Research Center to study the chemical and physical characteristics of the suspended particulate matter in Cleveland, measurements have been made of the particle size distributions at five different locations. The results of this study has shown the following:

1. Mass median diameters of Cleveland suspended particulates are in the range from about 2 to 7 micrometers depending upon the wind direction relative to source types. This is an order-of-magnitude larger than previously published work.

2. About two-thirds of the total suspended particulate matter in Cleveland is smaller than 7 micrometers in diameter. Almost half of this is in the submicron range. The composite distributions at each site are lognormal and are dependent on location and type of environment.

3. Junge-type number size distributions, derived from the mass distribution assuming unit density spheres, are consistent with typical dirty continental aerosols.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 15, 1974,
770-18.

APPENDIX - DETAILED DESCRIPTION OF EACH SITE

Site	Compass direction	Description of environment
1	30° to 50°	Area contains an interstate highway with an interchange, some truck terminals, light manufacturing plants, and large open spaces.
1	180° to 190°	A hill is adjacent to the site; heavy industry is about 3/4 kilometer away.
1	230° to 250°	The industrial valley of Cleveland is located here with steel mills, coke ovens, and assorted heavy industry; a large pile of iron ore is within 0.1 kilometer.
1	340° to 360°	Area contains an asphalt plant and petroleum related industry.
2	30° to 50°	Area contains residential neighborhood and a mixture of light manufacturing plants.
2	180° to 190°	Area contains residential neighborhood and a maxture of light manufacturing plants.
2	230° to 250°	The industrial valley of Cleveland is 3/4 to $1\frac{1}{2}$ kilometers away.
2	340° to 360°	Area contains a high school, heavily travelled street, steel fabrication, light industry, and manufacturing plants.
3	30° to 50°	A school and residential neighborhood are located here.
3	180° to 190°	Area contains commercial and residential neighborhood; a foundry is $3\frac{1}{2}$ kilometers away
3	230° to 250°	Area contains a hospital, a residential neighborhood, and a park comprised of open spaces and vegetation.
3	340° to 360°	Area is a residential neighborhood.
4	30° to 50°	Area is residential and commercial with an industrial complex $4\frac{1}{2}$ to 8 kilometers away.

4	180° to 190°	Area is residential and commercial.
4	230° to 250°	Area is residential and commercial.
4	340° to 360°	Area is residential and commercial.
5	30° to 50°	Area contains light industry and small commercial buildings.
5	180° to 190°	Highly commercial area; industrial valley 1½ to 2½ kilometers away.
5	230° to 250°	Commercial and office buildings of commercial center in Cleveland.
5	340° to 360°	Area contains office buildings, a railroad yard, lake shipping area; and an interstate highway with interchanges.

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TABLE I. - SUMMARY OF SUSPENDED PARTICULATE AND SIZE DISTRIBUTION DATA

AT FIVE SITES IN CLEVELAND, OHIO DURING AUGUST AND SEPTEMBER, 1972

Date	Resultant wind direction, deg	Site 1	Site 2	Site 3	Site 4	Site 5	Site 1	Site 2	Site 3	Site 4	Site 5	Site 1	Site 2	Site 3	Site 4	Site 5
		Mass median diameter, μm					Standard geometric deviation					Total particulate concentration, μg m^3				
8-10	360	2.30	----	2.20	2.28	3.79	15.0	----	6.6	12.2	7.5	314	---	71	143	114
8-11	190	4.30	3.09	2.93	2.50	2.20	19.0	9.8	3.6	3.8	38.8	282	113	47	80	404
8-14	230	----	2.28	2.70	3.74	2.81	----	5.7	4.7	6.1	5.9	---	152	146	181	156
8-15	50	3.60	3.59	3.61	7.00	4.49	6.[illegible]	4.3	4.5	4.1	6.3	207	108	160	289	255
8-16	180	----	2.15	----	----	2.32	----	11.4	----	----	8.3	---	147	---	---	146
8-17	250	9.42	2.00	3.13	----	4.56	13.0	13.0	17.2	----	14.0	308	159	86	---	136
8-21	180	3.53	1.69	----	1.40	3.46	11.2	8.9	----	11.3	14.6	265	147	---	122	293
8-22	180	4.45	1.80	----	3.64	4.61	11.8	8.7	----	4.7	12.7	296	187	---	122	351
8-23	180	6.28	2.08	----	2.59	8.75	10.1	8.6	----	7.4	12.5	386	163	---	151	403
8-24	190	----	2.04	----	2.92	2.49	----	9.1	----	10.0	8.6	---	303	---	154	153
8-28	230	4.60	4.24	----	3.31	3.49	9.9	9.9	----	11.5	8.8	180	170	---	149	123
8-29	310	6.66	2.98	----	1.80	4.07	6.0	10.0	----	6.2	8.8	314	176	---	101	240
8-30	30	4.63	2.73	4.02	3.32	5.32	10.2	7.2	8.5	10.9	11.1	243	151	142	116	246
8-31	160	4.14	2.63	1.69	4.51	5.89	10.0	8.3	11.6	4.7	12.0	235	186	138	128	360
9-5	250	6.29	2.93	3.33	3.88	5.23	11.4	9.2	10.6	12.9	19.5	303	123	64	125	144
9-6	180	5.61	2.80	1.65	----	----	12.3	10.5	8.5	----	----	290	158	93	---	---
9-7	180	----	4.77	2.62	2.28	3.79	----	3.5	6.7	7.9	12.4	---	116	81	157	175
9-11	190	3.46	1.72	1.71	2.08	2.48	9.4	7.3	9.9	7.0	7.4	216	198	157	171	223
9-12	40	3.08	1.99	2.76	2.88	4.35	8.1	5.9	8.5	9.0	7	228	188	199	196	309
9-13	220	4.53	2.62	2.50	2.90	3.14	6.6	5.4	4.9	7.3	6.0	17[illegible]	151	94	141	127
9-14	340	4.69	2.01	3.64	3.07	6.26	10.0	17.9	5.1	4.9	9.4	174	82	72	74	236

TABLE II. - RESULTANT

WIND DIRECTIONS AT

THREE WIND STATIONS

Date	CLE	Site A	Site B
	Wind direction, deg		
5 6	210	210	214
5 7	40	22	18
5 8	40	28	29
5 11	260	301	282
5 12	50	31	32
5 13	170	176	192
5 14	180	183	207

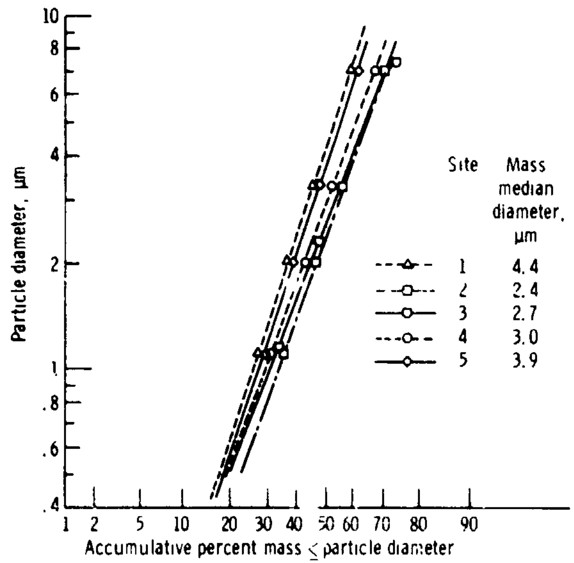

Figure 1. - Composite size distribution curve for August to September, 1972.

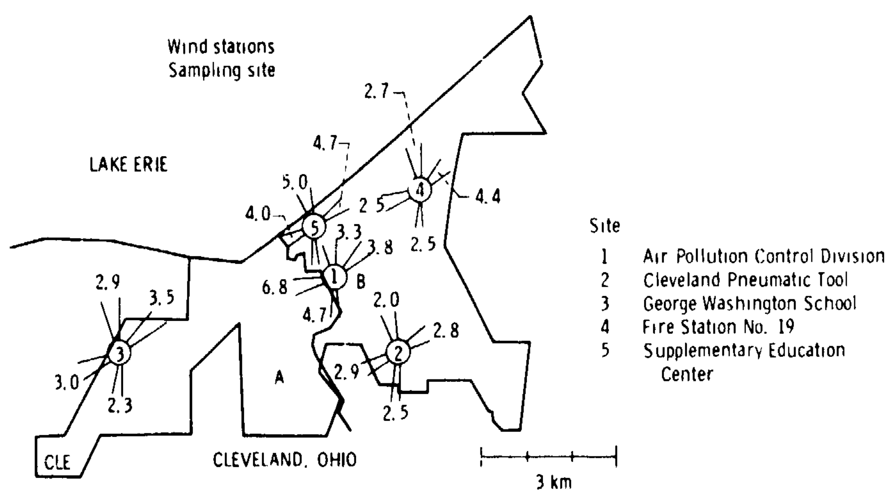

Figure 2. - Mass median diameter at each site as a function of prevailing resultant wind direction.

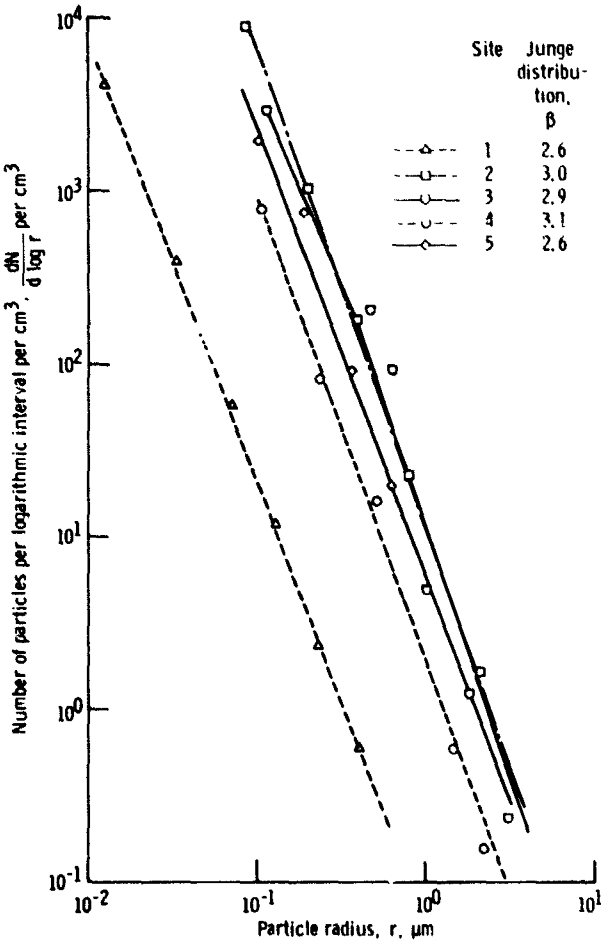

Figure 3. - Junge distribution.

NASA-Langley, 1974 E-8024